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AN ANALYSIS OF THE EFFECT OF A FLIGHT DIRECTOR ON PILOT PERFORMANCE IN A HELICOPTER HOVERING TASK

Timothy William Duffy

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THESIS

AN ANALYSIS OF THE EFFECT OF A FLIGHT DIRECTOR ON PILOT PERFORMANCE IN A HELICOPTER HOVERING TASK

by

Timothy William Duffy

March 1976

Thesis Advisor: R. A. Hess

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computer. The hovering task consisted of minimizing root mean square longitudinal and vertical deviation from an initial equilibrium position. Root mean square performance data and numerical pilot opinion ratings were obtained. These data indicated significant improvement in performance when the flight director was being utilized.

An Analysis of the Effect of a Flight Director on Pilot Performance in a Helicopter Hovering Task

by

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B.S., United States Naval Academy, 1968

Submitted in partial fulfillment of the
requirements for the degree of

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TABLE OF SYMBOLS

g	Acceleration of gravity, ft/sec^2.
h	Height deviation from reference position, ft.
$\dot{h}$	Vertical velocity, ft/sec.
I_y	Aircraft mass moment of inertia about the y stability axis, slug-ft^2.
M	Moment about y stability axis, ft-lbs.
m	Aircraft mass, slugs.
q	Aircraft pitching rate, radians/sec.
U_o	Aircraft reference velocity, ft/sec.
u	Perturbation vehicle velocity along x stability axis, ft/sec.
u_g	Horizontal turbulence velocity, ft/sec.
w	Perturbation vehicle velocity along z stability axis, ft/sec.
x	Longitudinal deviation from reference position, ft.
X	Force component along x stability axis, lbs.
Z	Force component along z stability axis, lbs.
δ_B	Cyclic pitch control input, displacement measured in feet at the pilot's hand.
δ_C	Collective pitch control input, displacement measured in feet at the pilot's hand.
θ	Aircraft pitch angle, radians.

The following stability derivatives are defined for straight, level, unaccelerated flight in the stability axis coordinate system.

$$X_q = \frac{1}{m} \frac{\partial X}{\partial q}\bigg|_o$$

$$X_u = \frac{1}{m} \frac{\partial X}{\partial u}\bigg|_o$$

$$X_w = \frac{1}{m} \frac{\partial X}{\partial w}\bigg|_o$$

$$X_{\delta_B} = \frac{1}{m} \frac{\partial X}{\partial \delta_B}\bigg|_o$$

$$X_{\delta_C} = \frac{1}{m} \frac{\partial X}{\partial \delta_C}\bigg|_o$$

$$Z_q = \frac{1}{m} \frac{\partial Z}{\partial q}\bigg|_o$$

$$Z_u = \frac{1}{m} \frac{\partial Z}{\partial u}\bigg|_o$$

$$Z_w = \frac{1}{m} \frac{\partial Z}{\partial w}\bigg|_o$$

$$Z_{\delta_B} = \frac{1}{m} \frac{\partial Z}{\partial \delta_B}\bigg|_o$$

$$Z_{\delta_C} = \frac{1}{m} \frac{\partial Z}{\partial \delta_C}\bigg|_o$$

$$M_q = \frac{1}{I_y} \frac{\partial M}{\partial q}\bigg|_o$$

$$M_u = \frac{1}{I_y} \left.\frac{\partial M}{\partial u}\right|_o$$

$$M_w = \frac{1}{I_y} \left.\frac{\partial M}{\partial w}\right|_o$$

$$M_{\dot{w}} = \frac{1}{I_y} \left.\frac{\partial M}{\partial \dot{w}}\right|_o$$

$$M_{\delta_B} = \frac{1}{I_y} \left.\frac{\partial M}{\partial \delta_B}\right|_o$$

$$M_{\delta_C} = \frac{1}{I_y} \left.\frac{\partial M}{\partial \delta_C}\right|_o$$

I. INTRODUCTION

In recent years much emphasis has been placed on the development of vertical take-off and landing aircraft. This heightened interest in the field has been brought about by air traffic congestion near large cities and by recent Navy reassessment of the role of the large aircraft carrier as opposed to smaller, more mobile aircraft carriers. Since a major advantage of VTOL aircraft is the capacity to operate from restricted spaces, it is mandatory that such aircraft be equipped with instrumentation that augments the human pilot to permit safe and reliable operation from these areas [Ref. 1]. One method of achieving this instrumentation has been to utilize electronic displays [Refs. 1, 2, and 3]. The purpose of this project was to evaluate the effect on pilot performance when a basic electronic display was augmented with a flight director.

II. METHOD OF INVESTIGATION

A hybrid computer was utilized to simulate the longitudinal flight dynamics of a UH-1H helicopter in the hover mode of operation. Conventional helicopter-type controls were used to generate inputs to the computer. The cyclic stick provided attitude control inputs and the collective control provided power inputs for height control.

The longitudinal motion of a helicopter can be depicted by the following equations of motion [Ref. 4].

$$\dot{u} = X_u u + X_w w + X_q q - g\theta + X_{\delta_B}\delta_B + X_{\delta_C}\delta_C - X_u u_g$$

$$\dot{w} = Z_u u + Z_w w + (U_o + Z_q)q + Z_{\delta_B}\delta_B + Z_{\delta_C}\delta_C - Z_u u_g$$

$$\dot{q} = (M_u + M_{\dot{w}} Z_u)u + (M_w + M_{\dot{w}} Z_w)w + [M_q + M_{\dot{w}}(U_o + Z_q)]q$$

$$+ (M_{\delta_B} + M_{\dot{w}} Z_{\delta_B})\delta_B + (M_{\delta_C} + M_{\dot{w}} Z_{\delta_C})\delta_C - (M_u + M_{\dot{w}} Z_u)u_g$$

$$\dot{\theta} = q$$

$$\dot{h} = -w + U_o\theta$$

These equations incorporate the following assumptions:

1. The vehicle is idealized as a rigid airframe to which is attached a rotor.
2. The rotor is described by its tip path plane whose orientation determines the propulsive and aerodynamic forces and moments.
3. No rotor degrees of freedom are considered other than control inputs which serve to describe instantaneous tip path plane orientation.
4. All coupling between longitudinal and lateral motion is ignored.
5. Linearized small perturbation theory is used to describe the motion about a horizontal reference flight path.

Table I lists the values for the stability derivatives used in the simulation. Elimination of those values that were zero and recognition of the fact that in the hover mode, $U_o = 0$, led to the following equations of motion:

$$\dot{u} = X_u u + X_w w + X_q q - g\theta + X_{\delta_B} \delta_B + X_{\delta_C} \delta_C - X_u u_g$$

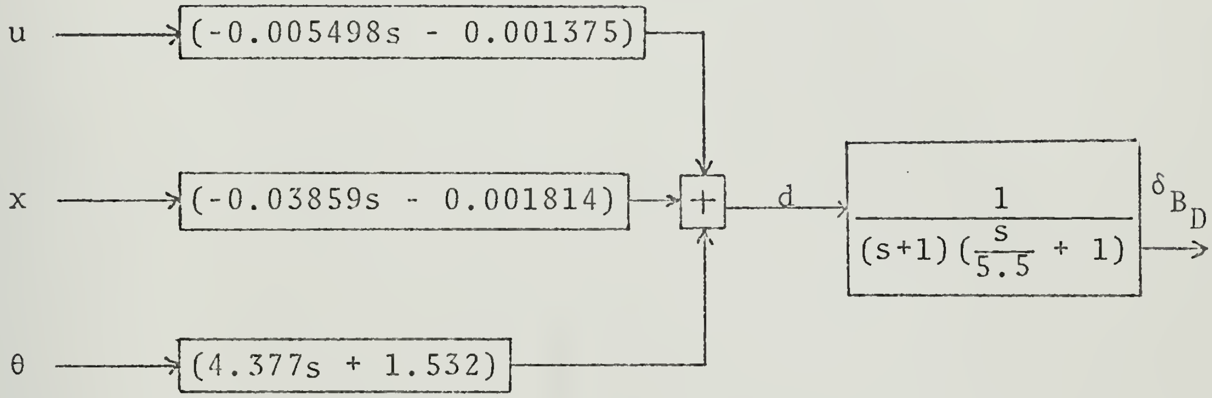
$$\dot{w} = Z_u u + Z_w w + Z_q q + Z_{\delta_B} \delta_B + Z_{\delta_C} \delta_C - Z_u u_g$$

$$\dot{q} = M_u u + M_w w + M_q q + M_{\delta_B} \delta_B + M_{\delta_C} \delta_C - M_u u_g$$

$\dot{\theta} = q$

$\dot{h} = -w$

The flight director law to be evaluated in this simulation can be represented in transfer function form by the following:



It can be shown from the preceding representation that

$$\ddot{\delta}_{B_D} + 6.5\,\dot{\delta}_{B_D} + 5.5\,\delta_{B_D} = 5.5d$$

where δ_{B_D} = commanded cyclic control in feet at pilot's hand.

The vehicle equations of motion were amplitude scaled and programmed on the analog portion of the hybrid computer. The hybrid computer gave real time solutions to the equations of motion, generated the baseline and flight director cockpit displays, and computed RMS performance data for each display. The horizontal turbulence, whose power spectrum is shown in Table II, was represented as

the sum of five sine waves, shown in Table III. The amplitudes and frequencies of these sinusoids were chosen so that the distribution of power with frequency of the sum of the sine waves closely approximated that of the spectrum of Table II [Ref. 5].

III. DESCRIPTION OF APPARATUS

A hybrid computer was utilized to (1) determine real time solutions to the helicopter longitudinal equations of motion, (2) generate the baseline and flight director displays and (3) compute performance data. The hybrid computer consisted of a Scientific Data Systems SDS 9300 digital computer, a Comcor CI-5000 analog computer, and an Adage AGT/10 graphics display. The digital computer controlled the analog computer and the graphics terminal. The digital program is listed in Appendix A. A schematic of the analog computer set-up is shown in Appendix B. Control inputs generated by the pilot were fed directly to the analog computer by means of gear driven potentiometers attached to the cyclic and collective controls. Figure 1 shows the physical arrangement of the helicopter controls and the cockpit display. The spring restrained cyclic stick was linear in displacement with respect to applied force (Fig. 2). The collective lever required a small force of 0.5 lb. to overcome a friction lock, but was otherwise free to travel.

IV. DESCRIPTION OF DISPLAY

The basic display utilized in the precision hovering task is shown in Figure 3. The symbol representing the position of the nose of the helicopter with respect to the horizon remained fixed in the center of the display. The square pad traversed vertically on the screen and served as a sensitive position indicator. The pad therefore provided information similar to that which the pilot would obtain by looking at the ground from the cockpit. When the pad was at the center of the screen and superimposed on the aircraft symbol, the helicopter was positioned over the reference point. As the helicopter moved 25 feet forward and rearward with respect to the reference hovering position, the pad moved one inch toward the bottom and top of the display respectively. The height deviation indicator was located at the lower left of the display. It consisted of a horizontal bar which traveled vertically up or down at the rate of 50 feet deviation from reference per inch of display indicator movement. This was a "fly to" device since as the bar moved up, the proper response was to pull up on the collective control to move the bar back to the reference position.

The basic display was augmented with a flight director indicator by entering the appropriate input data to the digital computer. The flight director was symbolized by

a "T-bar" which grew out of the aircraft symbol in the center of the pad and was scaled such that one foot of commanded cyclic motion produced one inch of director movement. It was also a "fly-to" device in that as the pad moved toward the top of the display, the T-bar would extend downward indicating that the pilot should ease the aircraft nose below the horizon and fly to the pad. As the helicopter approached the reference position, the T-bar would gradually recede in length until the horizontal position of the T coincided with the aircraft symbol.

V. EXPERIMENTAL PLAN

Volunteer pilots with Navy fleet experience in helicopters were utilized as test subjects to evaluate the effectiveness of a flight director display in the hover mode of operation of a UH-1H helicopter. All subjects had been inactive with respect to flying for over a year, but had previously held instrument qualifications in helicopters. Due to this lack of recent flight time and the unfamiliarity of the subjects with the simulator, it was assumed that each subject's performance would improve significantly as the number of training runs increased, until a steady-state level of performance was attained. This assumption proved to be valid, as in all cases the subject's deviation from optimum performance exhibited the characteristics of an exponential decay function that asymptotically approached each subject's maximum performance level. Optimum performance was defined to be minimum root mean square longitudinal and height deviation from the reference point.

Prior to the beginning of each training session, all subjects were informed of the task requirements, and the mechanics of the operation of the simulator. The pilots were instructed to maintain hovering position at the reference point and to maintain altitude in gusty air. The reference point was the center of a pad presented on the cockpit display. The hovering altitude was 40 feet.

Additionally a visual picture of the display (Fig. 3) was shown and thoroughly explained.

The display used in the simulation was 6.5 inches wide and 7.5 inches high. A nominal eye-to-display distance of 30 inches was used. The physical arrangement of the cockpit and display are shown in Figure 1.

All test subjects were trained extensively on both the baseline and flight director displays. The majority of training time for the first three subjects was spent on the baseline display since this proved to be the most difficult to master. Subject four, however, performed quite well initially with the baseline display, but required more training on the flight director display. This was due to a recurrent misinterpretation of the flight director.

In order to facilitate the learning process, each subject was informed of his RMS longitudinal and height deviation after each run. This proved to be more beneficial to the pilots than the actual parameters for pitch, pad size, and height deviation shown in Figure 3. Strip chart recordings of all the variables of interest were also made during the training sessions. This permitted the monitoring of any large instantaneous control inputs and subsequent large variations in performance data.

After the test subject achieved his maximum performance level, a formal data session was held. Each subject completed ten runs on the baseline display and ten runs on

the director display in the following manner. Five runs were completed with the baseline display and then five runs performed with the director display. A short break was then taken and the above sequence was repeated. The subject was not informed of his performance on any run until the entire data session was completed.

VI. RESULTS AND CONCLUSIONS

Table IV lists the root mean square performance data for all test subjects. Figures 4 through 11 graphically depict the performance data obtained in both modes of operation. For each subject, the mean value is indicated, as well as plus and minus one standard deviation.

In each case the difference in performance between the flight director mode of operation and the unaugmented mode was substantial. All pilots showed a marked decrease in longitudinal and vertical excursions from the hovering reference position when utilizing the flight director display. RMS position errors diminished by 16 to 45% longitudinally, and 17 to 39% vertically. Although the height deviation indicator was not equipped with a flight director, the decrease in vertical excursions was considered to be of major significance. The purpose of the flight director was to decrease longitudinal excursions in the hovering condition. This was to be accomplished by presenting the information the pilot normally collects by visually scanning the separate electro-mechanical cockpit instruments as a single cyclic control command. Intuitively, this would reduce the pilot's workload. The marked decrease in _vertical_ deviations was indicative of the reduction in workload for the pilot in controlling _longitudinal_ motion.

Typical time histories of all variables monitored (u, x, θ, q, h, $\dot{h}$, δ_B, δ_C) for both modes of operation, as well as the horizontal turbulence, are shown in Figures 12 and 13. These analog records graphically depict the decrease in control inputs required to accomplish the task. In addition to the reduction in longitudinal and vertical excursions and decrease in control inputs, Figures 4 through 11 show another significant effect of utilizing the flight director. The marked decrease in standard deviations observed was considered to be of major importance. Table V shows the pilot ratings given to each mode of operation. These ratings were obtained from the revised Cooper-Harper Rating System shown in Table VI [Ref. 6]. As can be readily seen, the flight director system consistently achieved a superior rating.

Pilot comments indicated that the flight director was definitely an aid in achieving optimum performance, and that it decreased pilot workload significantly. However, all pilots reported that it was difficult to perceive movement of the flight director when close to the center of the pad. This problem could be alleviated by incorporation of a variable gain feature on the director.

In conclusion, it can be said that utilization of the flight director in the precision hovering task significantly improved pilot performance. Since one of the primary requirements of VTOL vehicles is the ability to operate from confined spaces, it is imperative that any instrumentation

used to achieve improved mean performance also provide minimum standard deviation from that mean in order to ensure safe and reliable operation. The results of this evaluation have shown that utilization of the flight director resulted in improvements in both of these key parameters.

TABLE I

UH-1H Normalized Longitudinal Stability Derivatives Used in the Simulation

X_u	=	-0.0093397	1/sec
X_w	=	-0.00041791	1/sec
X_q	=	19.296	ft/sec
Z_u	=	-0.0021356	1/sec
Z_w	=	-0.40395	1/sec
Z_q	=	1.5145	ft/sec
M_u	=	0.00095595	1/sec-ft
M_w	=	-0.0014526	1/sec-ft
M_q	=	-2.0295	1/sec
$M_{\dot{w}}$	=	0.0	1/ft
X_{δ_B}	=	12.472	$1/sec^2$
X_{δ_C}	=	0.0018737	$1/sec^2$
Z_{δ_B}	=	-0.30802	$1/sec^2$
Z_{δ_C}	=	-96.066	$1/sec^2$
M_{δ_B}	=	-1.2797	$1/ft\text{-}sec^2$
M_{δ_C}	=	0.00024129	$1/ft\text{-}sec^2$

TABLE II

Turbulence Spectrum for Hover

$$\Phi_{u_g u_g}(\omega) = \frac{2\sigma^2_{u_g} L_u}{U_0} \frac{1}{1 + (L_u \omega / U_0)^2} \text{ ft}^2\text{rad/sec}^2$$

σ_{u_g} = 5 ft/sec

L_u/U_0 = 3.33 sec*

---

* Although $U_0 = 0$ and the "frozen turbulence" hypothesis is, strictly speaking, no longer valid, the general form of the turbulence spectrum above is retained. For example, one can consider $U_0 = 5$ ft/sec, $L_u = 16.65$ ft.

TABLE III

Sinusoidal Turbulence Representation

Sine Wave	Amplitude (ft/sec)	Frequency (rad/sec)
1	4.472	0.140
2	3.536	0.349
3	2.236	0.628
4	2.738	1.396
5	2.236	3.0

TABLE IV

Simulation Root Mean Square Performance Data

	BASELINE				DIRECTOR			
SUBJECT	A	B	C	D	A	B	C	D
x	+6.380	9.522	12.270	12.848	5.357	5.395	6.700	8.586
(ft)	++1.241	1.714	4.823	3.532	0.649	0.837	1.270	1.749
u	1.659	2.074	2.648	2.724	1.329	1.542	1.964	1.696
(ft/sec)	0.260	0.338	0.802	0.500	0.198	0.138	0.409	0.291
θ	0.02835	0.02902	0.03543	0.03089	0.02416	0.02848	0.03489	0.02669
(rad)	0.00369	0.00573	0.00999	0.00501	0.00302	0.00268	0.00638	0.00413
q	0.01927	0.02040	0.02226	0.01522	0.01459	0.01783	0.02236	0.01476
(rad/sec)	0.00303	0.00406	0.00540	0.00298	0.00176	0.00206	0.00463	0.00235
h	7.144	7.392	11.496	10.906	5.930	5.965	6.959	6.692
(ft)	1.234	1.457	3.401	3.270	0.835	1.562	2.283	1.608
$\dot{h}$	4.509	2.916	3.187	1.915	3.822	2.488	2.501	1.330
(ft/sec)	0.926	0.612	0.780	0.682	0.359	0.589	0.615	0.357
δ_B	0.03810	0.04157	0.04361	0.02957	0.02835	0.03513	0.04475	0.02999
(ft)	0.00631	0.00842	0.00975	0.00615	0.00340	0.00430	0.00964	0.00405
δ_C	0.04857	0.02285	0.02607	0.00968	0.03987	0.02036	0.02066	0.00650
(ft)	0.01333	0.00511	0.00841	0.00394	0.00438	0.00628	0.00424	0.00215

+MEAN ++ STANDARD DEVIATION

TABLE V

Cooper-Harper Pilot Ratings

SUBJECT	RATING	
	BASELINE	DIRECTOR
A	A6	A4
B	A6	A5
C	A6	A3
D	A4	A3

TABLE VI

The Revised Cooper-Harper Scale

CONTROLLABLE CAPABLE OF BEING CONTROLLED OR MANAGED IN CONTEXT OF MISSION, WITH AVAILABLE PILOT ATTENTION	**ACCEPTABLE** MAY HAVE DEFICIENCIES WHICH WARRANT IMPROVEMENT, BUT ADEQUATE FOR MISSION. PILOT COMPENSATION, IF REQUIRED TO ACHIEVE ACCEPTABLE PERFORMANCE, IS FEASIBLE.	**SATISFACTORY** MEETS ALL REQUIREMENTS AND EXPECTATIONS, GOOD ENOUGH WITHOUT IMPROVEMENT CLEARLY ADEQUATE FOR MISSION.	EXCELLENT, HIGHLY DESIRABLE	A1
			GOOD, PLEASANT, WELL BEHAVED	A2
			FAIR. SOME MILDLY UNPLEASANT CHARACTERISTICS. GOOD ENOUGH FOR MISSION WITHOUT IMPROVEMENT.	A3
		UNSATISFACTORY RELUCTANTLY ACCEPTABLE. DEFICIENCIES WHICH WARRANT IMPROVEMENT. PERFORMANCE ADEQUATE FOR MISSION WITH FEASIBLE PILOT COMPENSATION.	SOME MINOR BUT ANNOYING DEFICIENCIES. IMPROVEMENT IS REQUESTED. EFFECT ON PERFORMANCE IS EASILY COMPENSATED FOR BY PILOT.	A4
			MODERATELY OBJECTIONABLE DEFICIENCIES. IMPROVEMENT IS NEEDED. REASONABLE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION.	A5
			VERY OBJECTIONABLE DEFICIENCIES. MAJOR IMPROVEMENTS ARE NEEDED. REQUIRES BEST AVAILABLE PILOT COMPENSATION TO ACHIEVE ACCEPTABLE PERFORMANCE.	A6
	UNACCEPTABLE DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT. INADEQUATE PERFORMANCE FOR MISSION EVEN WITH MAXIMUM FEASIBLE PILOT COMPENSATION.		MAJOR DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT FOR ACCEPTANCE. CONTROLLABLE. PERFORMANCE INADEQUATE FOR MISSION, OR PILOT COMPENSATION REQUIRED FOR MINIMUM ACCEPTABLE PERFORMANCE IN MISSION IS TOO HIGH.	U7
			CONTROLLABLE WITH DIFFICULTY. REQUIRES SUBSTANTIAL PILOT SKILL AND ATTENTION TO RETAIN CONTROL AND CONTINUE MISSION.	U8
			MARGINALLY CONTROLLABLE IN MISSION. REQUIRES MAXIMUM AVAILABLE PILOT SKILL AND ATTENTION TO RETAIN CONTROL.	U9
UNCONTROLLABLE CONTROL WILL BE LOST DURING SOME PORTION OF MISSION.			UNCONTROLLABLE IN MISSION.	10

Figure 1. Apparatus.

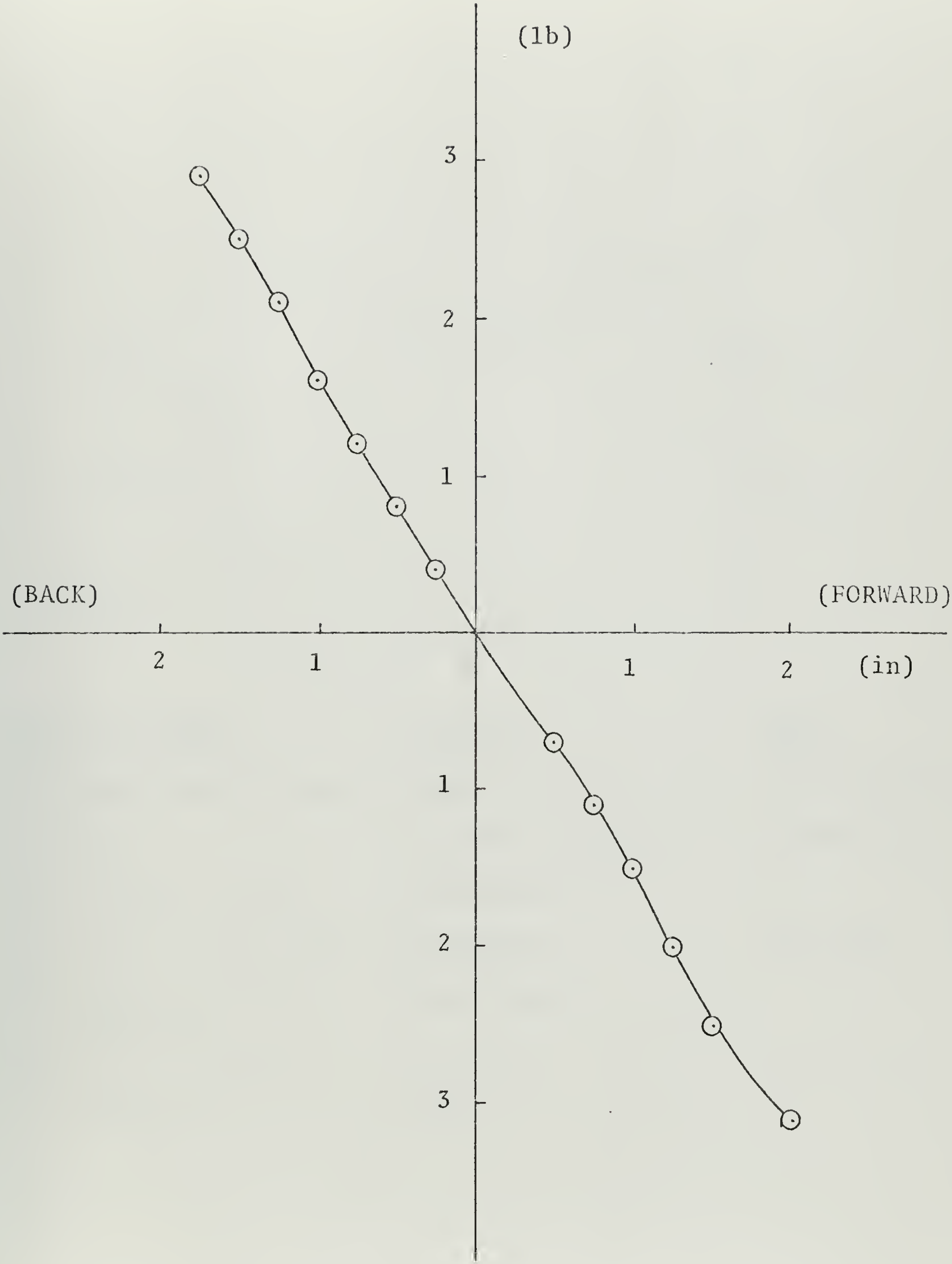
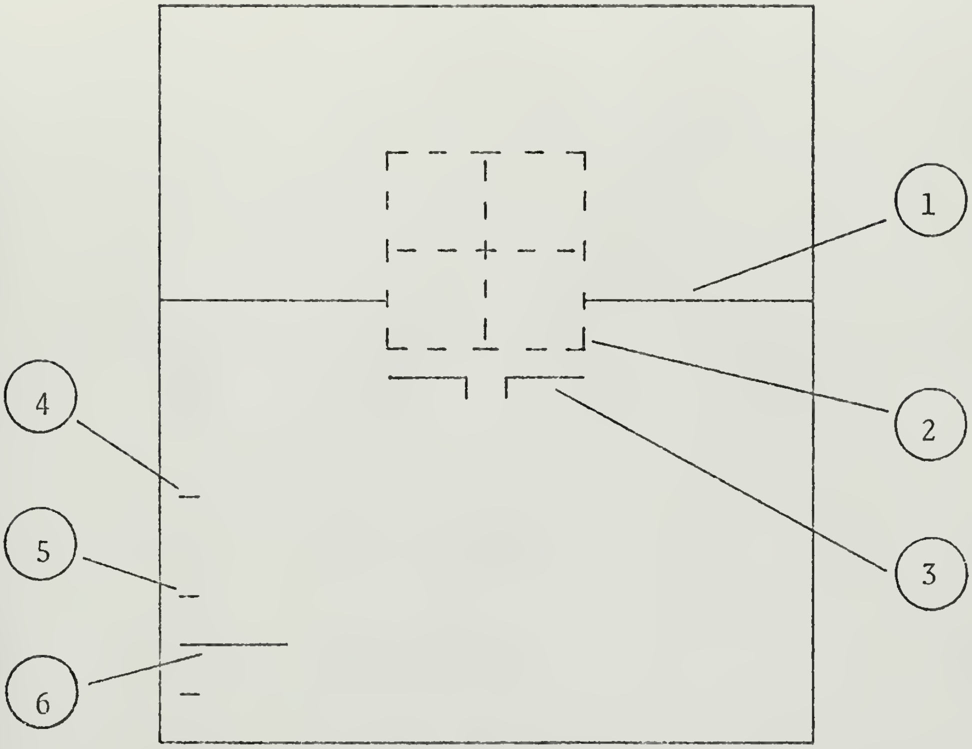
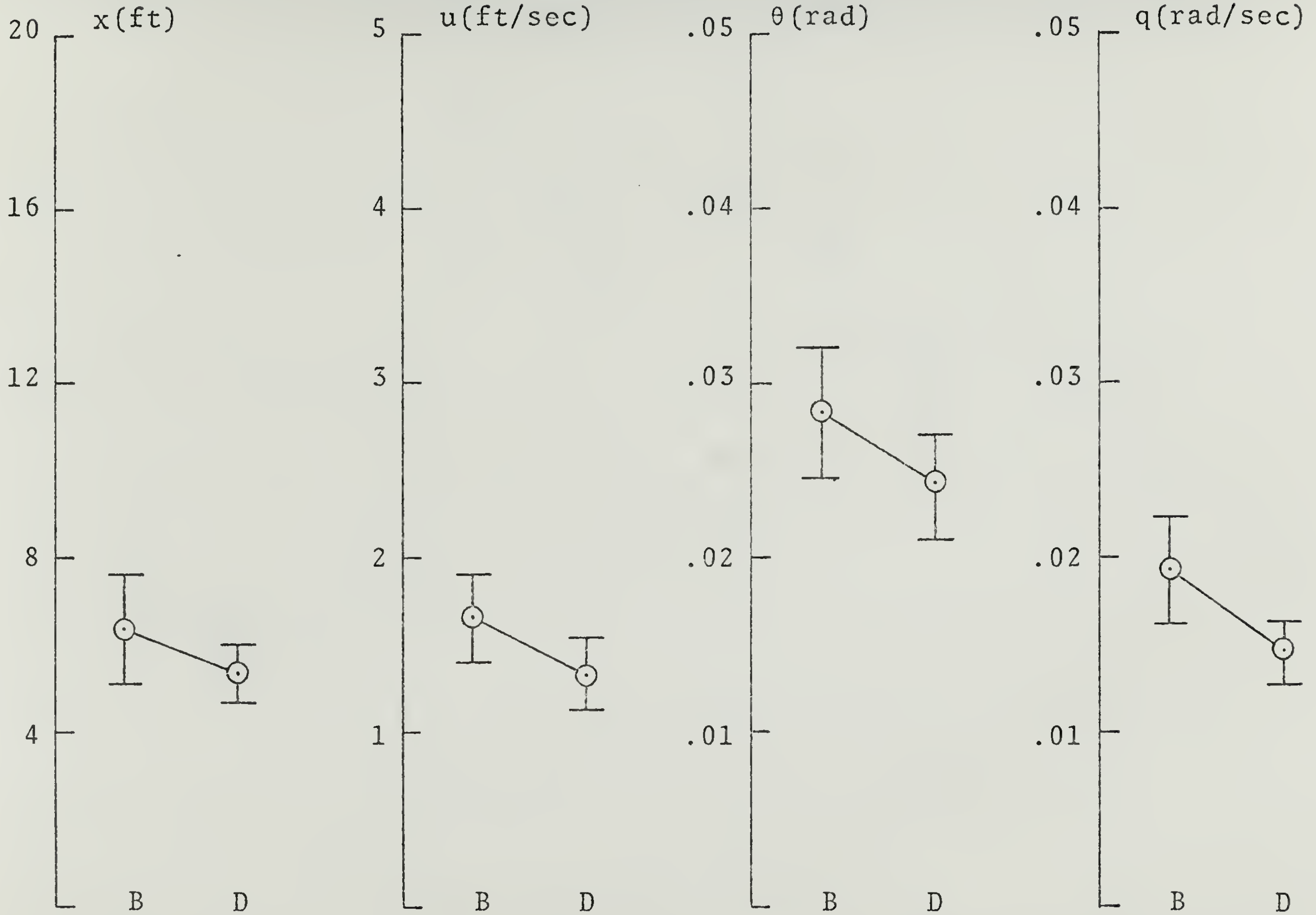


Figure 2. Cyclic Stick Force vs. Displacement.



Display Element	Function	Units
1. Artificial Horizon	Pitch Attitude	20 degrees/inch
2. Pad	Position Indicator	25 feet/inch
3. Aircraft Symbol	Stationary	
4. Height Indicators	Stationary	±50 feet
5. Reference Height Position	Stationary	
6. Height Deviation Indicator	Altitude Error	50 feet/inch

Figure 3. Cockpit Display.



B - Baseline display. D - Flight director display.

Figure 4. Performance Data, Subject A.

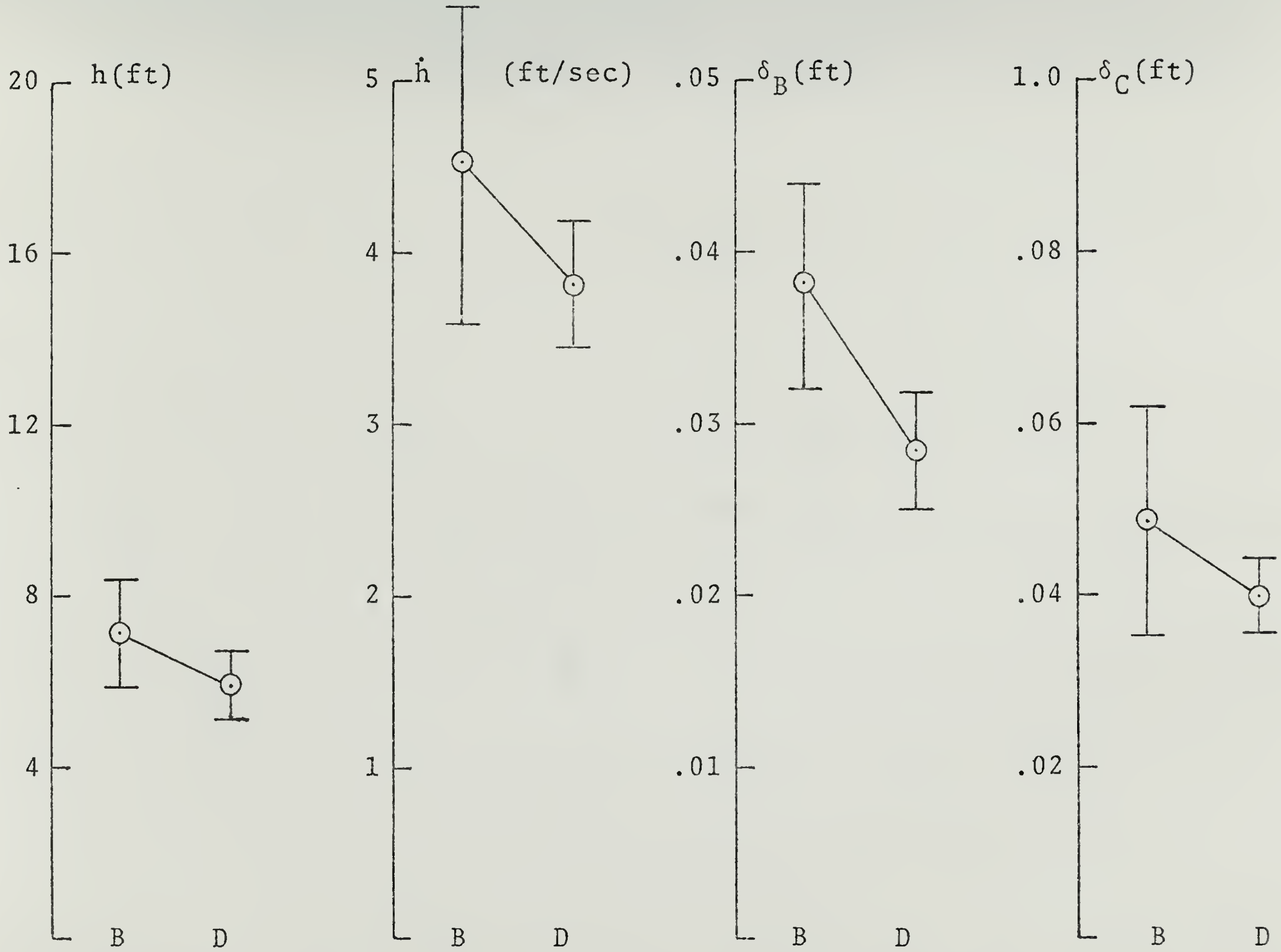


Figure 5. Performance Data, Subject A.

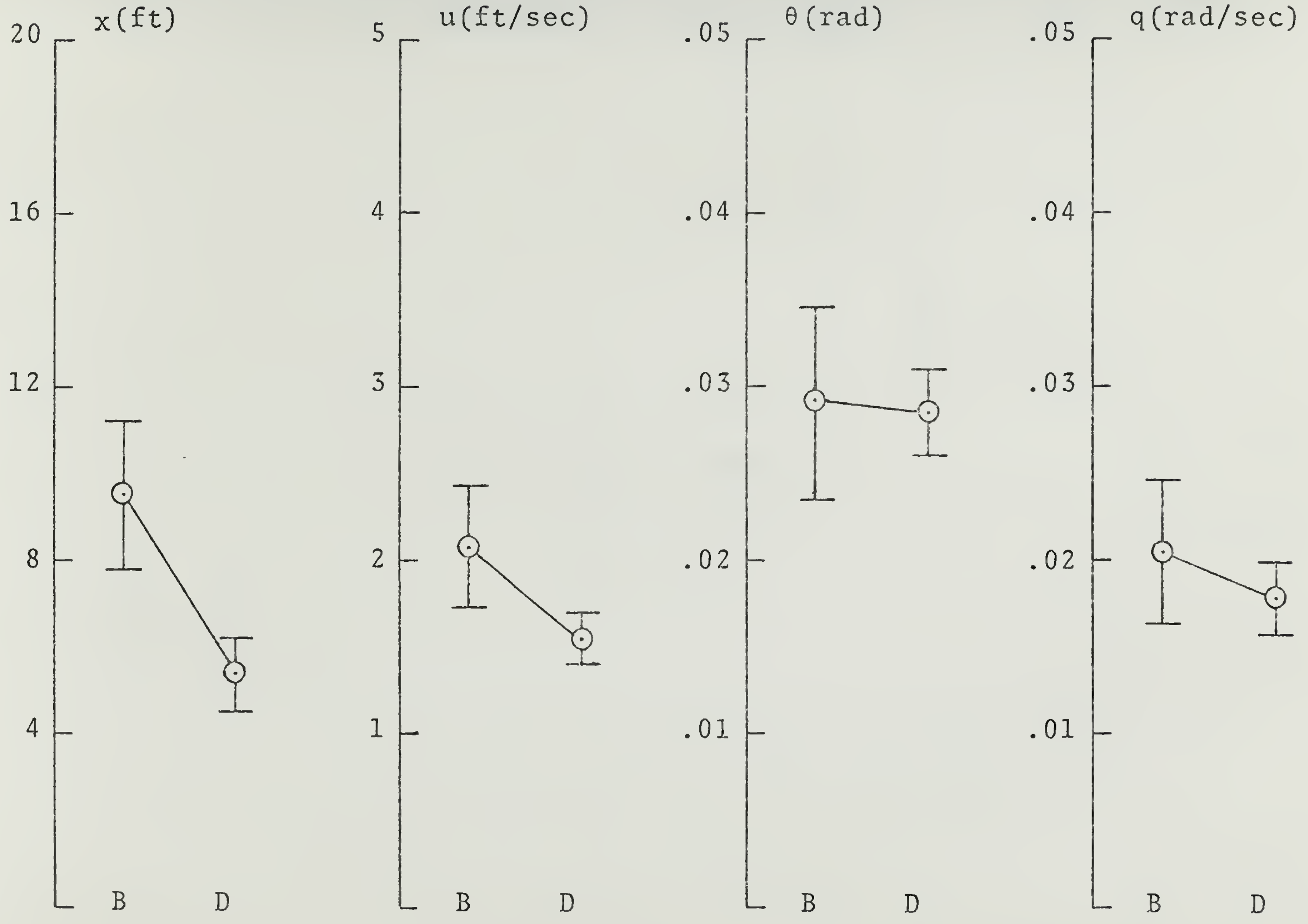


Figure 6. Performance Data, Subject B.

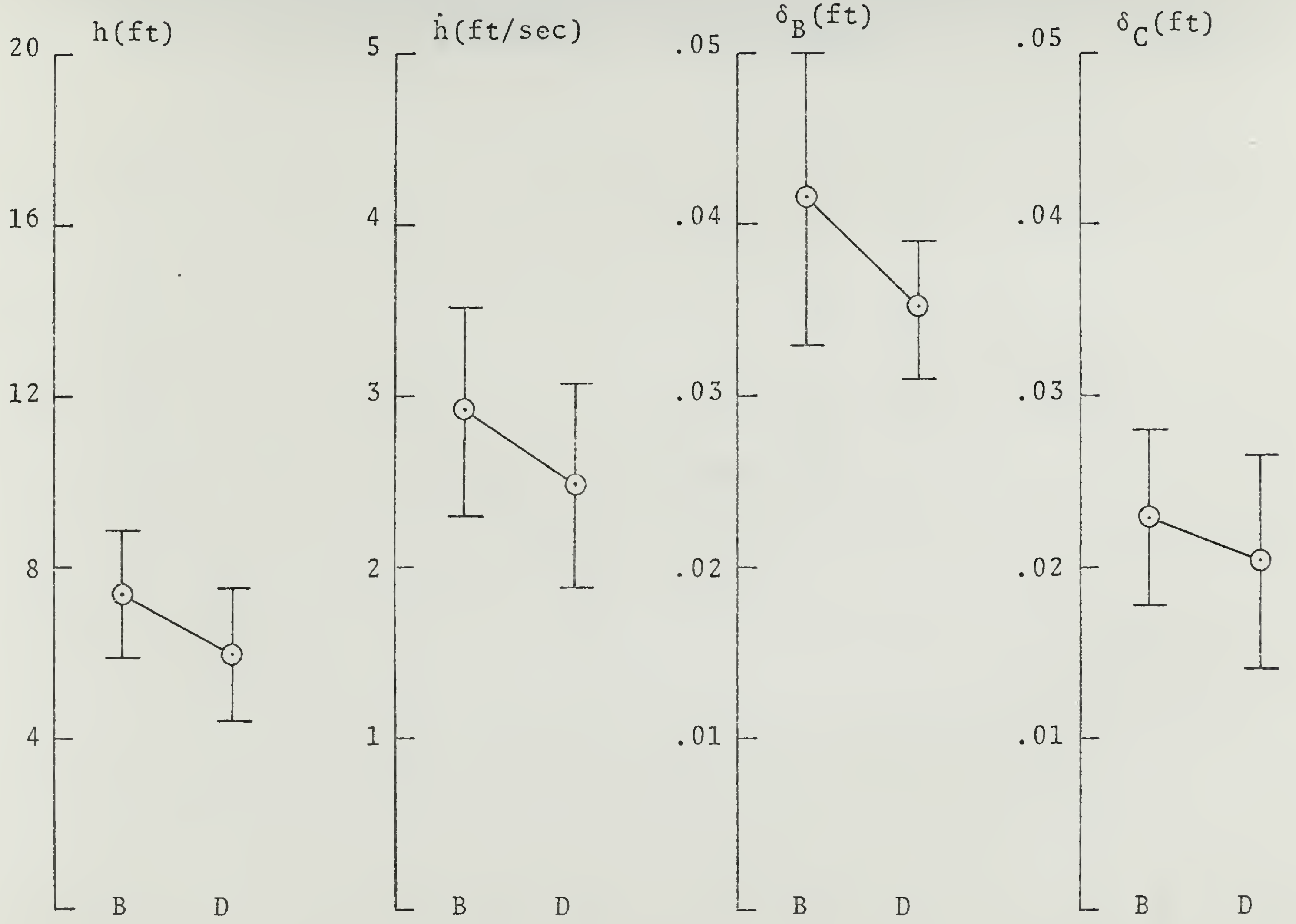


Figure 7. Performance Data, Subject B.

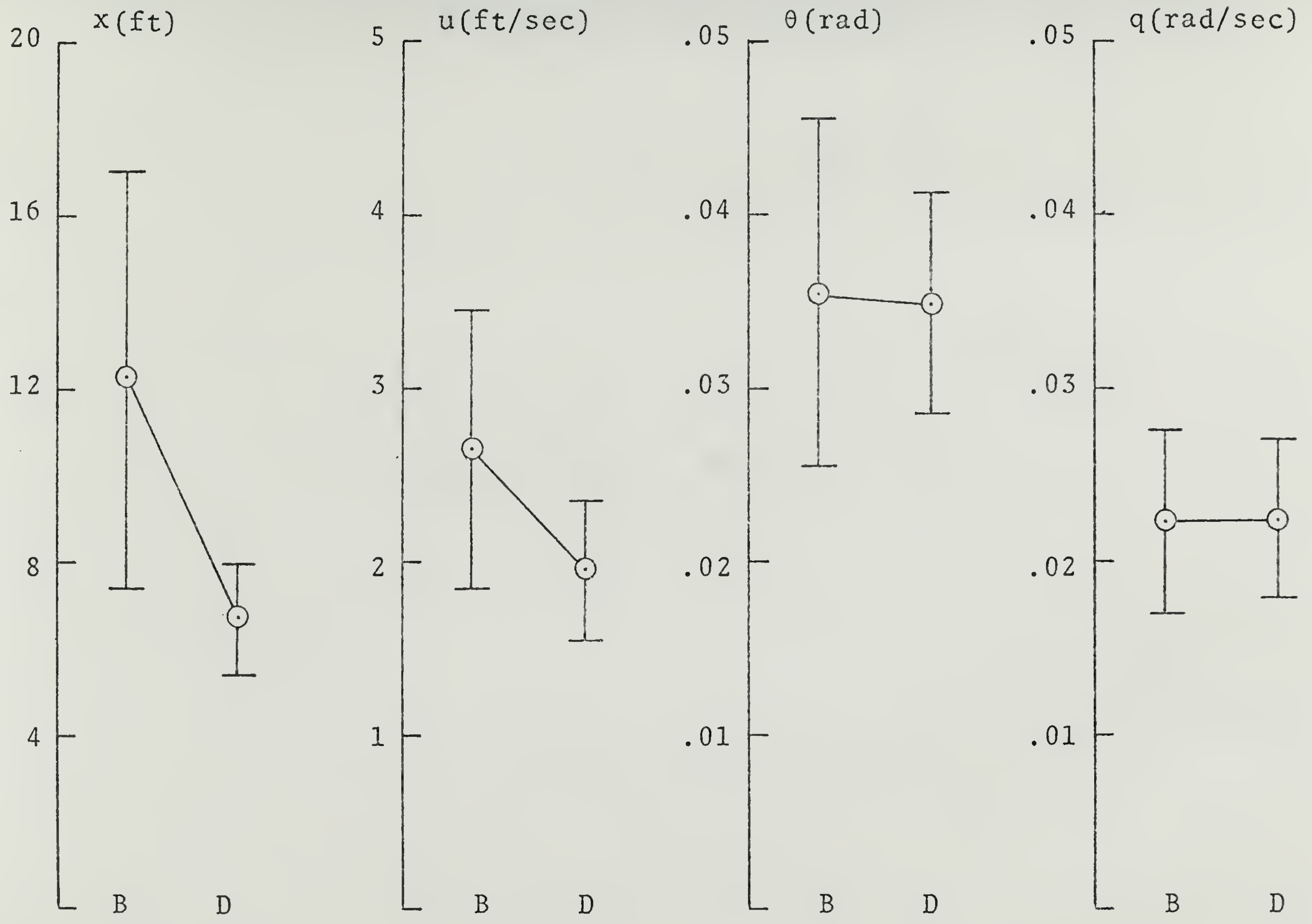


Figure 8. Performance Data, Subject C.

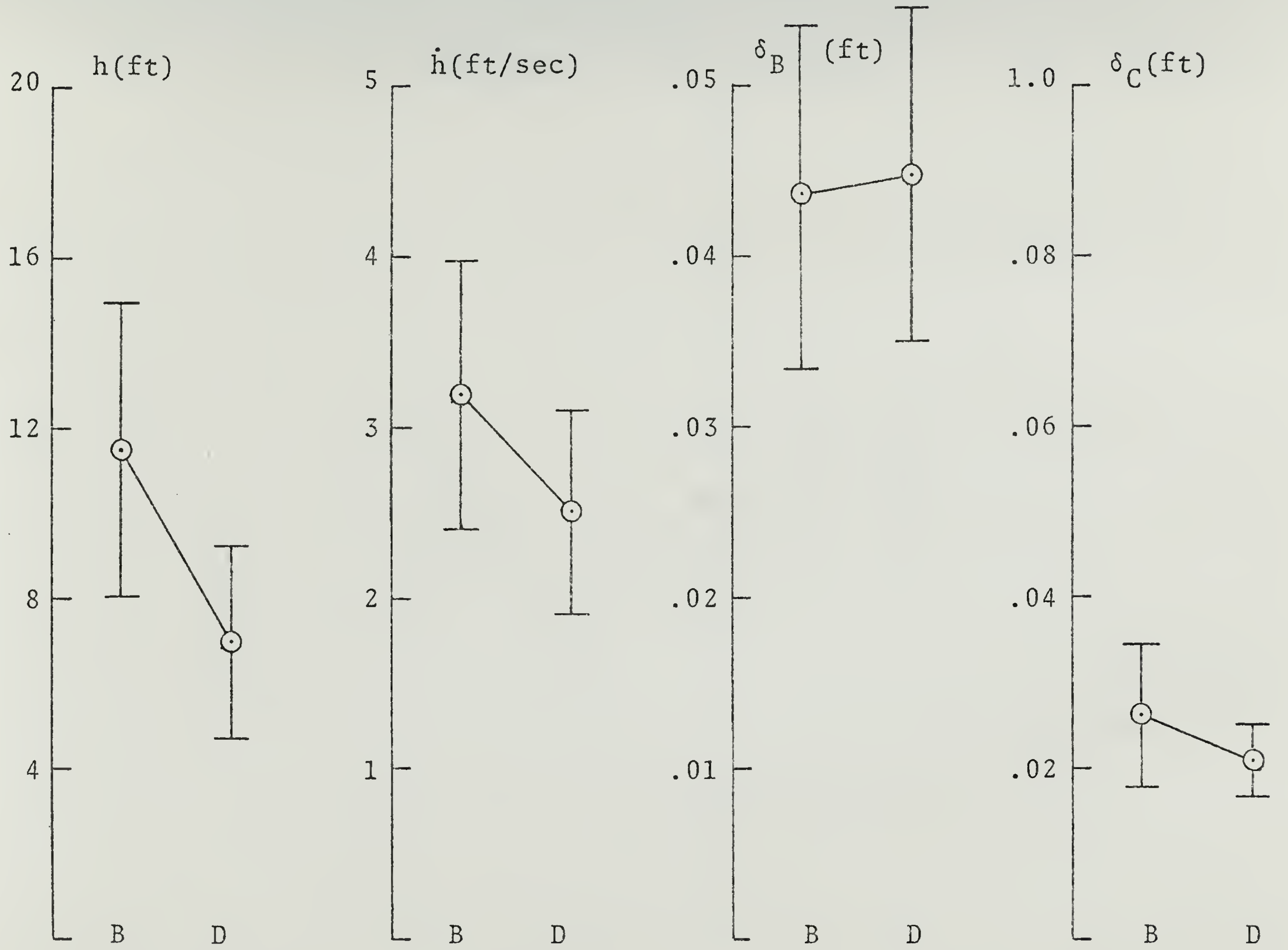


Figure 9. Performance Data, Subject C.

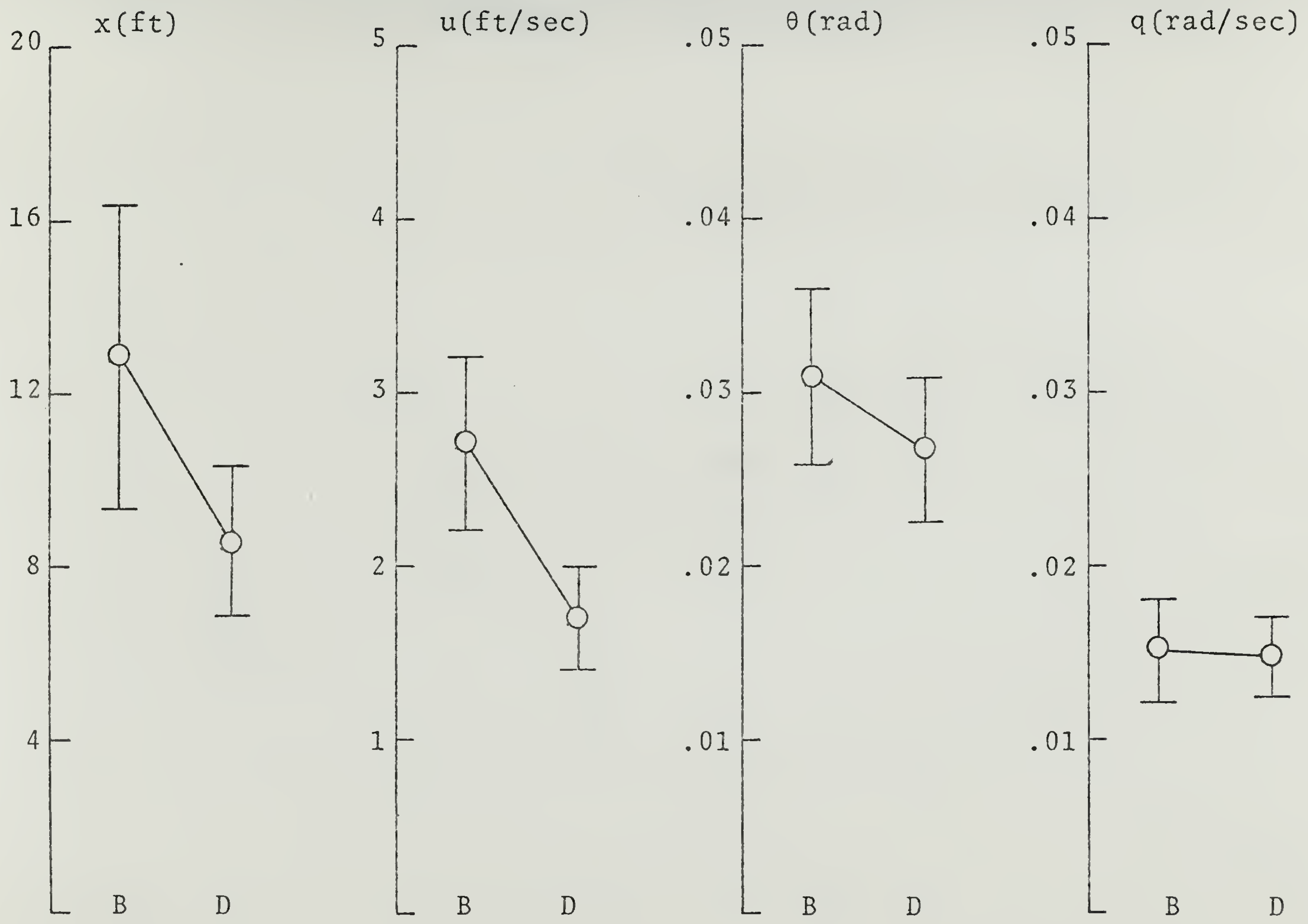


Figure 10. Performance Data, Subject D.

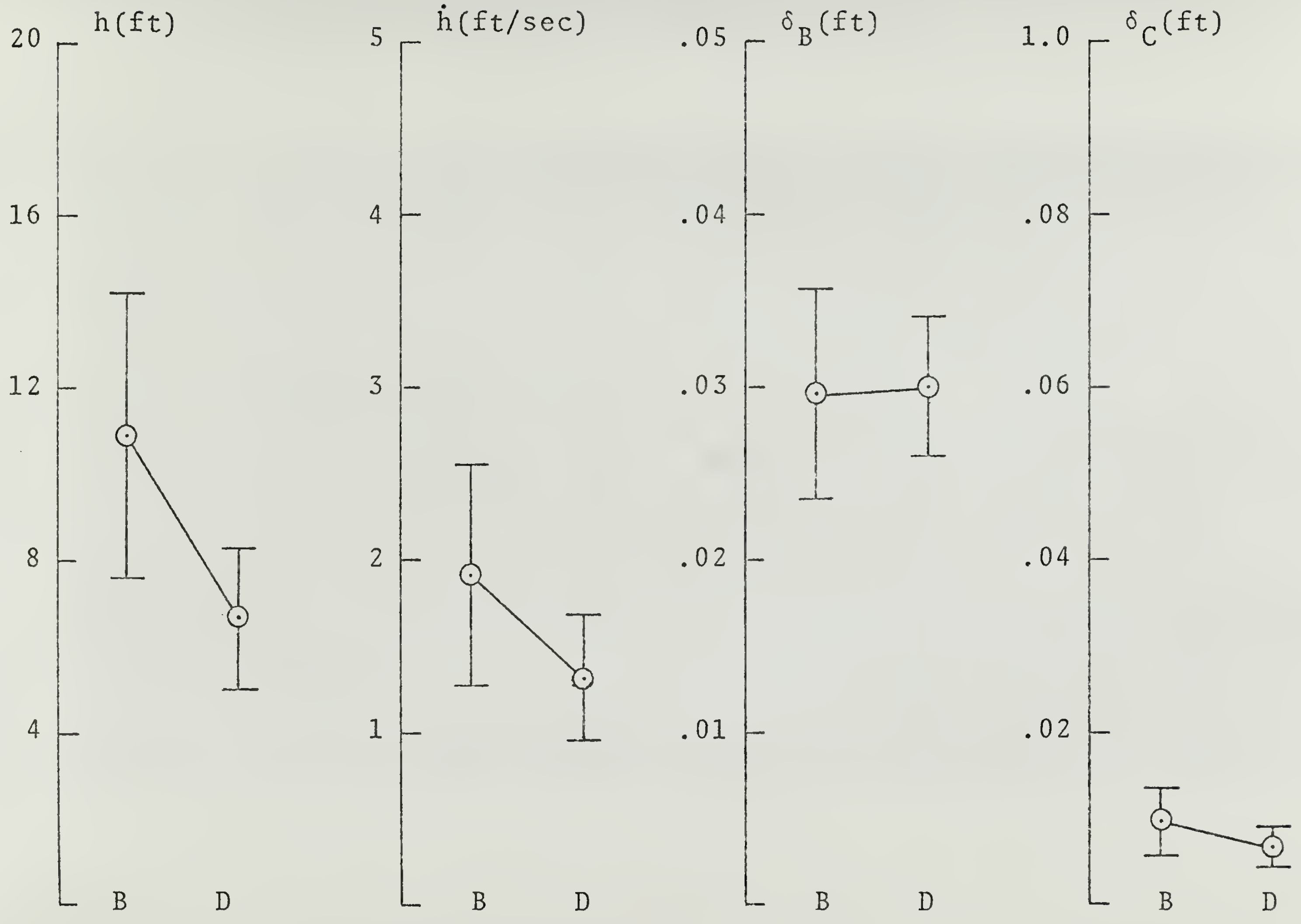


Figure 11. Performance Data, Subject D.

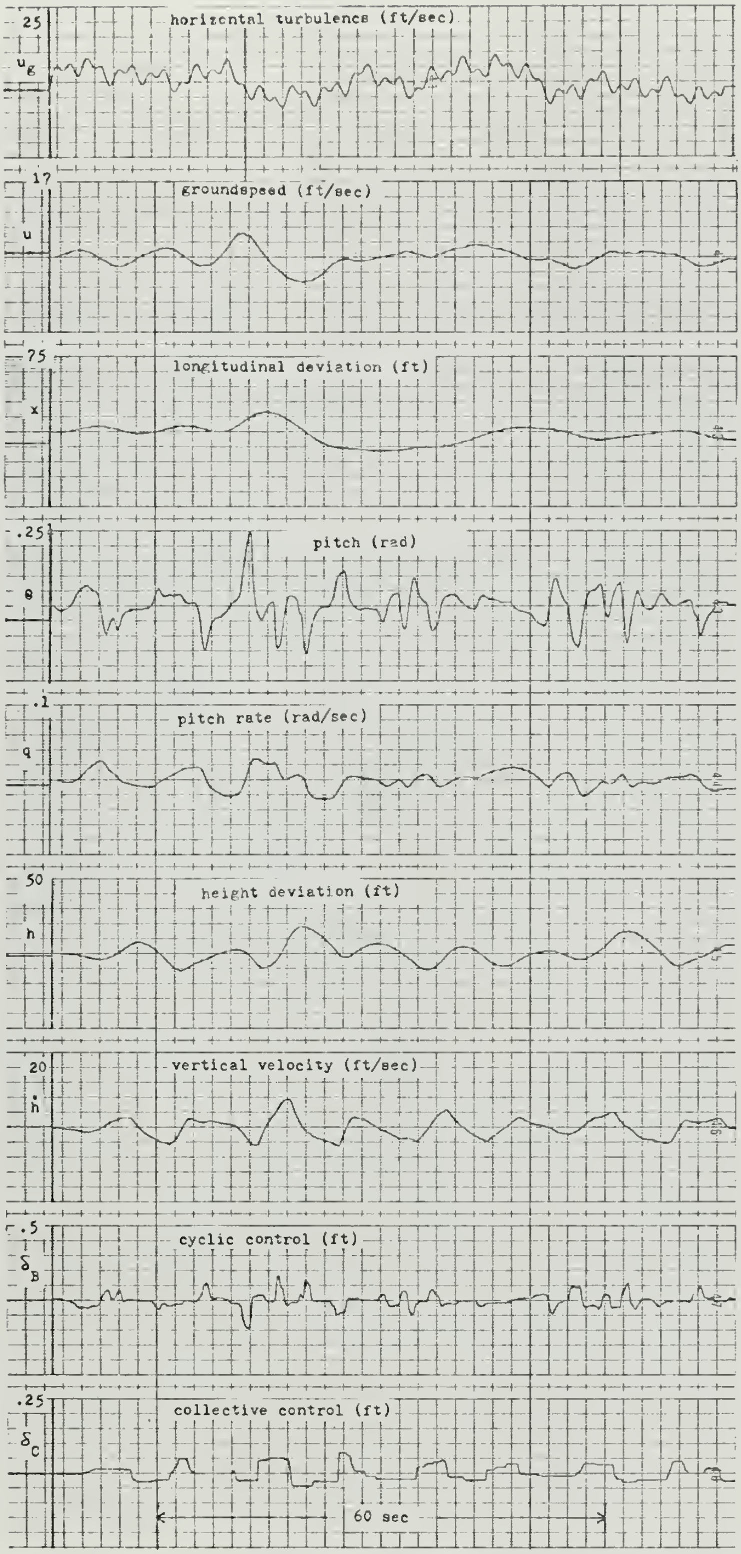


Figure 12. Time Histories of Monitored Variables for Subject B, Using the Baseline Display.

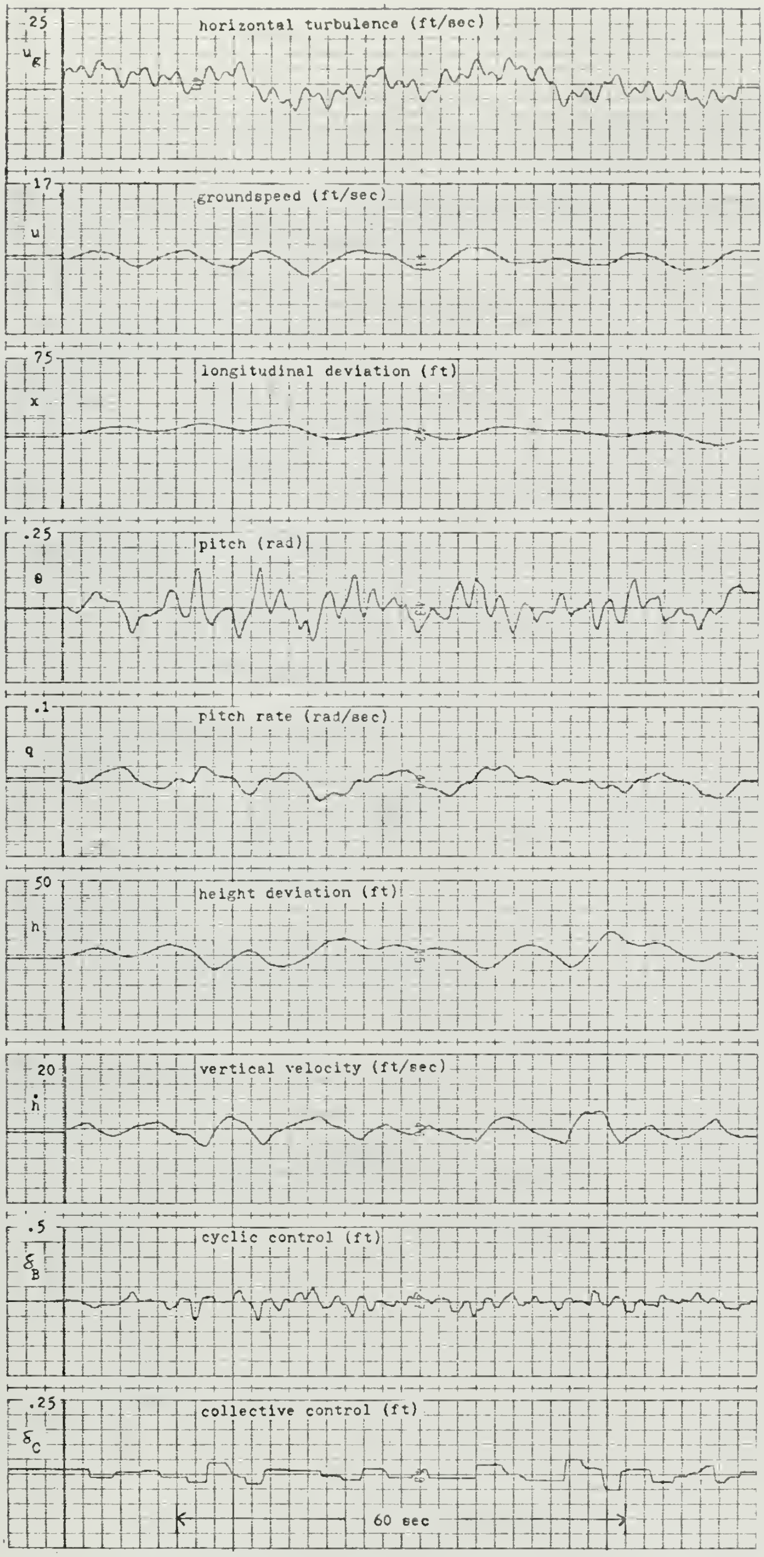


Figure 13. Time Histories of Monitored Variables for Subject B, Using the Flight Director Display

APPENDIX A THE DIGITAL PROGRAM

```
      INTEGER IGD(6),FRAME(12),GSLP(17),ACREF(20),HORIZ(25),
     1PAD(10)
      DIMENSION ITD(60), ITEXT(12), UG(1500)
      NAMELIST MODE,CYD,COD,E16,E17,E21,E23,E24,E25,SC
      OUTPUT(102)'SCALE THE DISPLAY,   SC= '
      INPUT(101)
      FRAME(1) = IHEAD(0,6)
C
      DO 110 I=2,12
      READ (5,260) X,Y,IDM
      X = SC*X
      Y = SC*Y
  110 FRAME(I) = IPACK(X,Y,IDM)
C
      GSLP(1) = IHEAD(0,7)
C
      DO 120 I=2,12
      READ (5,260) X,Y,IDM
      X = SC*X
      Y = SC*Y
  120 GSLP(I) = IPACK(X,Y,IDM)
C
      ACREF(1) = IHEAD(0,9)
C
      DO 130 I=2,20
      READ (5,260) X,Y,IDM
      X = SC*X
      Y = SC*Y
  130 ACREF(I) = IPACK(X,Y,IDM)
C
      HORIZ(1) = IHEAD(0,8)
C
      DO 140 I=2,5
      READ (5,260) X,Y,IDM
  140 HORIZ(I) = IPACK(X,Y,IDM)
C
      PAD(1) = IHEAD(1,8)
C
      DO 150 I=2,6
      READ (5,260) X,Y,IDM
      X = SC*X
      Y = SC*Y
  150 PAD(I) = IPACK(X,Y,IDM)
C
      A1 = 4.472
      A2 = 3.536
      A3 = 2.236
      A4 = 2.738
      A5 = 2.236
      OMU1 = .14
      OMU2 = .349
      OMU3 = .628
      OMU4 = 1.396
      OMU5 = 3.0
      UDR = 9.95
      T = 0.
C
C     TAKE CARE OF PERIPHERAL EQUIPMENT
C
      OUTPUT(102)'ENGAGE PATCHBOARDS,SELECT INPUT CONTROL,EX
     1ECUTE GATED, AND SET SENSE SWITCH'
      CALL SETPOT (4HP000,.1135,4HP001,.0037,4HP003,.2270,4H
     1P004,.1195,4HP006,.3000,4HP012,.0178,4HP013,.0687,4HP0
     214,.4732,4HP015,.1500,4HP022,.1010,4HP027,.6399,4HP030
     3,.6420,4HP031,.3668,4HP032,.6800,4HP033,.3080,4HP034,.
     46500,4HP035,.5500,4HP037,.0003,4HP042,.1601,4HP050,.16
     525,4HP051,.0093,4HP052,.0242,4HP053,.4040,4HP054,.2179
     66,4HP055,.2030,4HP056,.4000,4HP057,.0060)
```

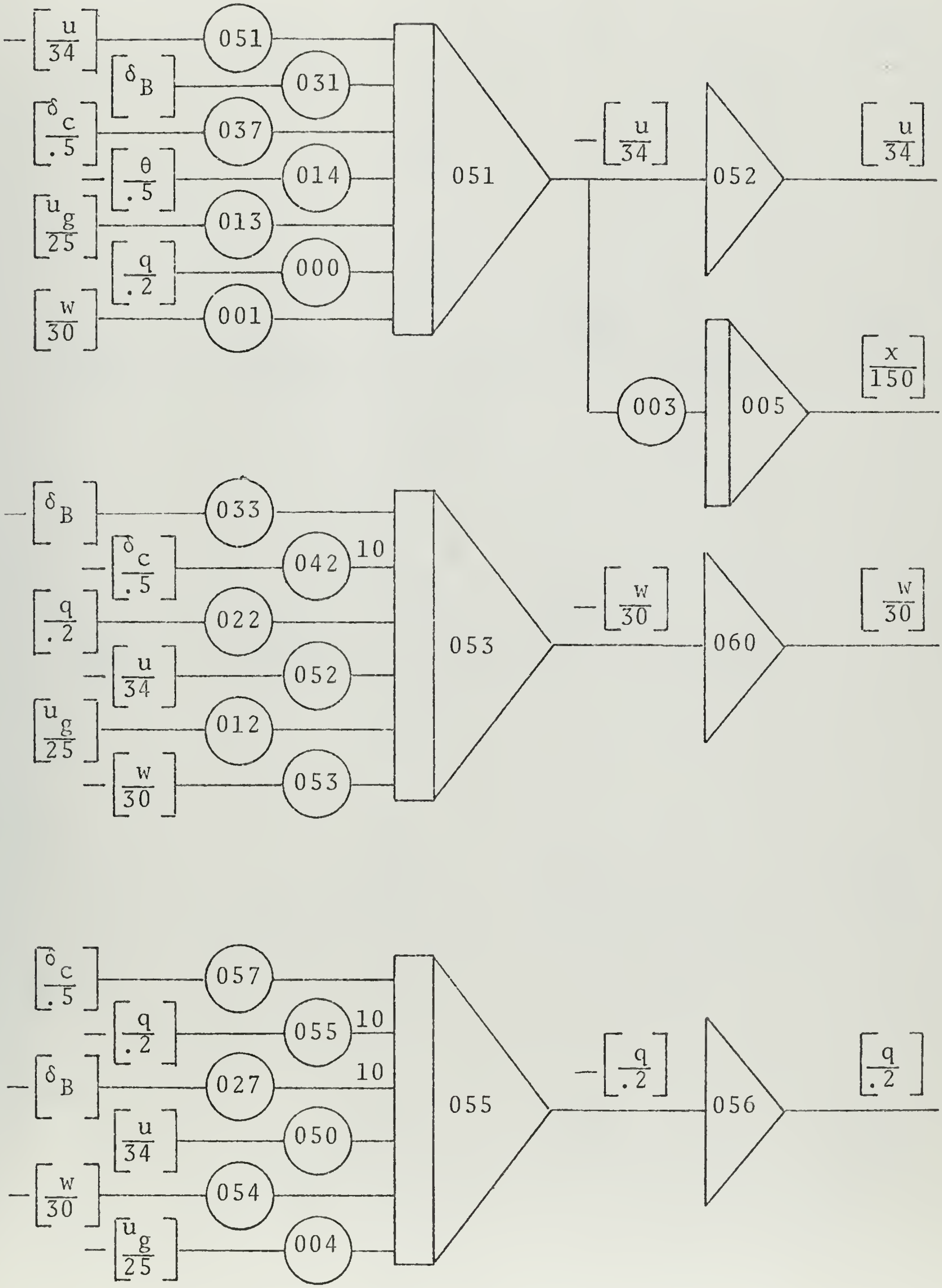
```
      IDEV = 1
  152 IF (SENSESWITCH(1)) 158,154
  154 IF (SENSESWITCH(2)) 156,152
  156 IDEV = 2
  158 OUTPUT(102)'SELECT CYCLIC AND COLLECTIVE DIRECTOR GAIN
     1,CYD=,COD='
      INPUT(101)
      CALL DGINIT (IDEV,IGD,6,IER)
      CALL DTINIT (IDEV,ITD,60,IER)
  160 OUTPUT(102)'SELECT DISPLAY MODE, MODE=1,2'
      INPUT(101)
      ENCODE (48,270,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,10,1,2,2,IER)
      ENCODE (48,280,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,12,1,2,2,IER)
      ENCODE (48,290,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,14,1,2,2,IER)
      ENCODE (48,300,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,16,1,2,2,IER)
      ENCODE (48,310,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,20,1,2,2,IER)
      ENCODE (48,320,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,22,1,2,2,IER)
      ENCODE (48,330,ITEXT)
      CALL TEXTO (IDEV,ITEXT,12,24,1,2,2,IER)
C
      DO 170 I=1,1500
      SU1 = OMU1*T
      SU2 = OMU2*T
      SU3 = OMU3*T
      SU4 = OMU4*T
      SU5 = OMU5*T
      UG(I) = (1./25.00)*(A1*SIN(SU1)+A2*SIN(SU2)+A3*SIN(SU3
     1)+A4*SIN(SU4)+A5*SIN(SU5))
      T = T+(1./UDR)
  170 CONTINUE
C
      T = -1./UDR
  175 IF (TEST(1).GT.0) GO TO 175
      CALL DTINIT (IDEV,ITD,60,IER)
      AB = 0.0
      AV = 0.
      AMSX = 0.
      AMSAS = 0.
      AMSP = 0.
      AMSQ = 0.
      AMSGS = 0.
      AMSGSD = 0.
      AMSDB = 0.
      AMSDC = 0.
C
      DO 180 I=6,25
      HORIZ(I) = 0
  180 CONTINUE
C
C
      DO 190 J=13,17
      GSLP(J) = 0
  190 CONTINUE
C
      IF (MODE.GT.1) GO TO 220
C
C     MODE 1, BASIC DISPLAY
C
      CALL GRAPHO (IDEV,FRAME,12,1,IER)
      CALL GRAPHO (IDEV,ACREF,20,2,IER)
      CALL WRITECLOCK (0)
      CALL RESET (500)
      CALL COMPUTE
      CALL STARTCLOCK
C
      DO 200 I=1,7200
```

```
      CALL READCLOCK (V)
      IF (V.GT.5400.) GO TO 210
      AB = AB+1.0
      UG1 = UG(I)
      CALL DAC (1,UG1)
      CALL ADK (0,AS,1,P,2,GS,3,Q,4,GSD,5,XPD,6,DB,7,DC)
      VAV = V-AV
      AMSX = ((XPD*XPD)*VAV+AMSX*AV)/V
      AMSAS = ((AS*AS)*VAV+AMSAS*AV)/V
      AMSP = ((P*P)*VAV+AMSP*AV)/V
      AMSQ = ((Q*Q)*VAV+AMSQ*AV)/V
      AMSGS = ((GS*GS)*VAV+AMSGS*AV)/V
      AMSGSD = ((GSD*GSD)*VAV+AMSGSD*AV)/V
      AMSDB = ((DB*DB)*VAV+AMSDB*AV)/V
      AMSDC = ((DC*DC)*VAV+AMSDC*AV)/V
      P = .2865*P
      GS = 0.4*GS
      Y = .1-P
      Y = SC*Y
      X1 = SC*.6
      X2 = SC*.125
      HORIZ(2) = IPACK(-X1,Y,0)
      HORIZ(3) = IPACK(-X2,Y,1)
      HORIZ(4) = IPACK(X2,Y,0)
      HORIZ(5) = IPACK(X1,Y,1)
      Y = -.2-GS
      Y = SC*Y
      X1 = SC*.57
      X2 = SC*.37
      GSLP(10) = IPACK(-X1,Y,0)
      GSLP(11) = IPACK(-X2,Y,1)
      GSLP(12) = IPACK(-X1,Y,1)
      XPD = 1.2*XPD
      X1 = SC*.2
      Y1 = SC*(-XPD+.3)
      Y2 = SC*(-XPD-.1)
      Y3 = (Y1+Y2)/2.
      PAD(2) = IPACK(-X1,Y1,0)
      PAD(3) = IPACK(X1,Y1,1)
      PAD(4) = IPACK(X1,Y2,1)
      PAD(5) = IPACK(-X1,Y2,1)
      PAD(6) = IPACK(-X1.Y1,1)
      PAD(7) = IPACK(0,Y1,0)
      PAD(8) = IPACK(0,Y2,1)
      PAD(9) = IPACK(-X1,Y3,0)
      PAD(10) = IPACK(X1,Y3,1)
      CALL GRAPHO (IDEV,GSLP,17,3,IER)
      CALL GRAPHO (IDEV,HORIZ,25,4,IER)
      CALL GRAPHO (IDEV,PAD,10,5,IER)
      AV = V
  200 CONTINUE
C
  210 CALL HOLD (500)
      CALL STOPCLOCK
      GO TO 250
C
C     MODE 2, FLIGHT DIRECTOR
C
  220 CALL GRAPHO (IDEV,FRAME,12,1,IER)
      CALL GRAPHO (IDEV,ACREF,20,2,IFR)
      CALL WRITECLOCK (0)
      CALL RESET (500)
      CALL COMPUTE
      CALL STARTCLOCK
C
      DO 230 I=1,7200
      CALL READCLOCK (V)
      IF (V.GT.5400.) GO TO 240
      AB = AB+1.0
      UG1 = UG(I)
      CALL ADK (0,AS,1,P,2,GS,3,Q,4,GSD,5,XPD,6,DB,7,DC,8,DB
     1D)
```

```
C
C
C    DIRECTOR LAWS ARE CREATED HERE
C
C
      UD = -.3175*AS+.00836*GSD+3.859*Q-16.087*P+12.472*DB+.
     12335*UG1
      UP = -.0055*UD-1.359*AS+.8754*Q+.766*P-.2721*XPD
      CALL DAC (1,UG1,3,UP)
      VAV = V-AV
      AMSX = ((XPD*XPD)*VAV+AMSX*AV)/V
      AMSAS = ((AS*AS)*VAV+AMSAS*AV)/V
      AMSP = ((P*P)*VAV+AMSP*AV)/V
      AMSQ = ((Q*Q)*VAV+AMSQ*AV)/V
      AMSGS = ((GS*GS)*VAV+AMSGS*AV)/V
      AMSGSD = ((GSD*GSD)*VAV+AMSGSD*AV)/V
      AMSDB = ((DB*DB)*VAV+AMSDB*AV)/V
      AMSDC = ((DC*DC)*VAV+AMSDC*AV)/V
      P1 = .2865*P
      GS1 = 0.4*GS
      Y = .1-P1
      Y = SC*Y
      X1 = SC*.6
      X2 = SC*.125
      HORIZ(2) = IPACK(-X1,Y,0)
      HORIZ(3) = IPACK(-X2,Y,1)
      HORIZ(4) = IPACK(X2,Y,0)
      HORIZ(5) = IPACK(X1,Y,1)
C
C
C     CYCLIC DIRECTOR LAW GOES HERE
C
C
      Y = 0.1-CYD*DBD*.2
      Y = SC*Y
      X1 = SC*.1
      HORIZ(6) = IPACK(0.0,X1,0)
      HORIZ(7) = IPACK(0.0,Y,1)
      HORIZ(8) = IPACK(-X1,Y,1)
      HORIZ(9) = IPACK(X1,Y,1)
      HORIZ(10) = IPACK(0.0,Y,1)
      Y = -.2-GS1
      Y = SC*Y
      X1 = SC*.57
      X2 = SC*.37
      GSLP(10) = IPACK(-X1,Y,0)
      GSLP(11) = IPACK(-X2,Y,1)
      GSLP(12) = IPACK(-X1,Y,1)
      XPD = 1.2*XPD
      X1 = SC*.2
      Y1 = SC*(-XPD+.3)
      Y2 = SC*(-XPD-.1)
      PAD(2) = IPACK(-X1,Y1,0)
      Y3 = (Y1+Y2)/2.
      PAD(3) = IPACK(X1,Y1,1)
      PAD(4) = IPACK(X1,Y2,1)
      PAD(5) = IPACK(-X1,Y2,1)
      PAD(6) = IPACK(-X1,Y1,1)
      PAD(7) = IPACK(0,Y1,0)
      PAD(8) = IPACK(0,Y2,1)
      PAD(9) = IPACK(-X1,Y3,0)
      PAD(10) = IPACK(X1,Y3,1)
C
C
C      COLLECTIVE DIRECTOR LAW GOES HERE
C
C
      Y = -.2
      Y = SC*Y
      X1 = SC*.3
      X2 = SC*.35
      X3 = SC*.25
```

```
      Y1 = SC*.2
      GSLP(13) = IPACK(-X1,-Y1,0)
      GSLP(14) = IPACK(-X1,Y,1)
      GSLP(15) = IPACK(-X2,Y,1)
      GSLP(16) = IPACK(-X3,Y,1)
      GSLP(17) = IPACK(-X1,Y,1)
      CALL GRAPHO (IDEV,GSLP,17,3,IER)
      CALL GRAPHO (IDEV,HORIZ,25,4,IER)
      CALL GRAPHO (IDEV,PAD,10,5,IER)
      AV = V
  230 CONTINUE
C
  240 CALL HOLD (500)
      CALL STOPCLOCK
  250 CONTINUE
C
C     THIS SECTION TAKES INTEGRATED SQUARE VALUES AND
C     GENERATES ROOT MEAN SQUARE PERFORMANCE VALUES.
C
      CALL DGINIT (IDEV,IGD,6,IER)
      RMSX = 150.*SQRT(AMSX)
      RMSAS = 34.*SQRT(AMSAS)
      RMSP = .5*SQRT(AMSP)
      RMSQ = .2*SQRT(AMSQ)
      RMSGS = 100.*SQRT(AMSGS)
      RMSGSD = 20.*SQRT(AMSGSD)
      RMSDB = SQRT(AMSDB)
      RMSDC = 0.5*SQRT(AMSDC)
      UDR = AB/90.
      WRITE (6,340) MODE
      WRITE (6,350) UDR
      WRITE (6,360) RMSX,RMSAS,RMSP,RMSQ,RMSGS,RMSGSD,RMSDB,
     1RMSDC
      GO TO 160
C
  260 FORMAT (2F10.4,I1)
  270 FORMAT ('          THIS IS A HELICOPTER TRACKING
     1   ')
  280 FORMAT ('      PROBLEM REQUIRING THE ADJUSTMENT OF
     1   ')
  290 FORMAT ('      POWER AND PITCH ATTITUDE TO MAINTAIN
     1   ')
  300 FORMAT ('      A STEADY HOVER IN TURBULENCE.
     1   ')
  310 FORMAT ('          WHEN READY TO BEGIN, PRESS THE
     1   ')
  320 FORMAT ('      RED BUTTON ON THE COLLECTIVE LEVER.
     1   ')
  330 FORMAT ('      THE TASK WILL LAST FOR 90 SECONDS.
     1   ')
  340 FORMAT ('0','DISPLAY MODE  ',I1/)
  350 FORMAT ('0','UPDATE RATE AVERAGED ',F8.5,' TIMES PER S
     1ECOND'/)
  360 FORMAT ('0','RMS LONGITUDINAL DEV       ',F8.5,' FT'/'
     10',
     1 'RMS GROUNDSPEED            ',F8.5,' FT/SEC'/'0',
     2 'RMS PITCH                  ',F8.5,' RAD'/'0',
     3 'RMS PITCH RATE             ',F8.5,' RAD/SEC'/'0',
     4 'RMS HEIGHT DEV             ',F8.5,' FT'/'0',
     5 'RMS VERTICAL VEL           ',F8.5,' FT/SEC'/'0',
     6 'RMS CYCLIC                 ',F8.5,' FT'/'0',
     7 'RMS COLLECTIVE             ',F8.5,' FT'///)
      END
```

APPENDIX B - THE ANALOG PROGRAM



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$\left[\frac{\delta_c}{.5}\right]$
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$\left[\frac{q}{.2}\right]$
$\left[\frac{w}{30}\right]$
051
031
037
014
013
000
001
051
$-\left[\frac{u}{34}\right]$
052
$\left[\frac{u}{34}\right]$
003
005
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$\left[\frac{q}{.2}\right]$
$-\left[\frac{u}{34}\right]$
$\left[\frac{u_g}{25}\right]$
$-\left[\frac{w}{30}\right]$
033
042
10
022
052
012
053
053
$-\left[\frac{w}{30}\right]$
060
$\left[\frac{w}{30}\right]$
$\left[\frac{\delta_c}{.5}\right]$
$-\left[\frac{q}{.2}\right]$
$-\left[\delta_B\right]$
$\left[\frac{u}{34}\right]$
$-\left[\frac{w}{30}\right]$
$-\left[\frac{u_g}{25}\right]$
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055
10
027
10
050
054
004
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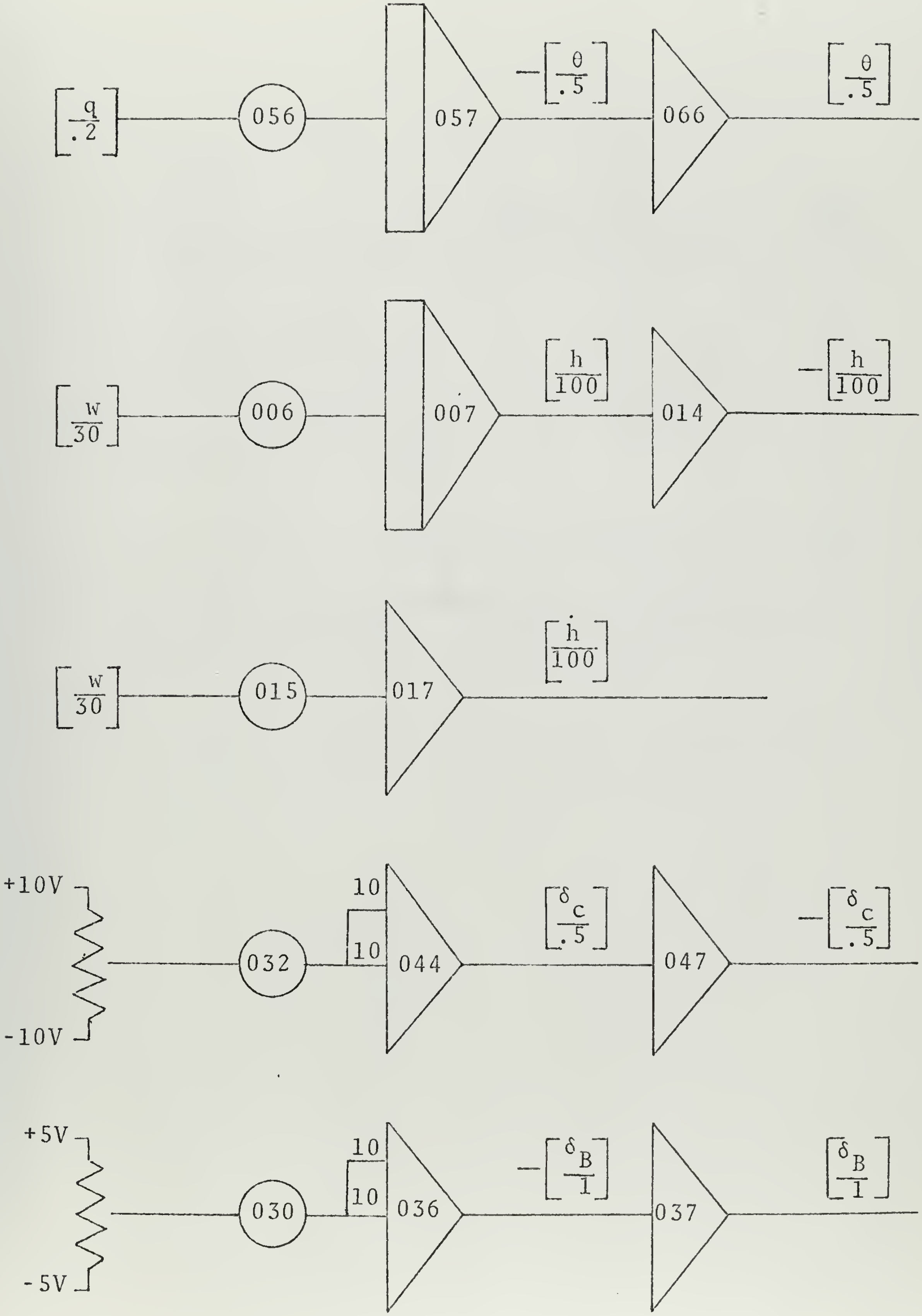
056
$\left[\frac{q}{.2}\right]$

[q/.2]
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017
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+10V
-10V
032
10
10
044
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047
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+5V
-5V
030
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10
036
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037
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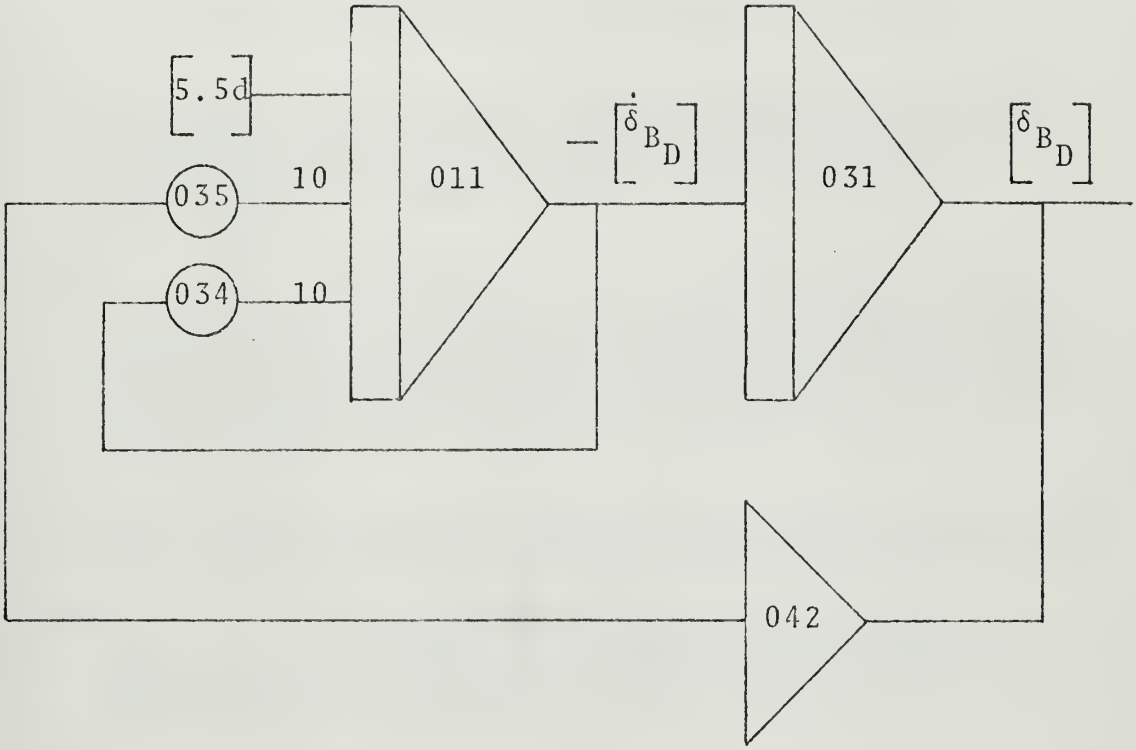
5.5d
$-\left[\dot{\delta}_{B_D}\right]$
$\left[\delta_{B_D}\right]$

LIST OF REFERENCES

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